Space Applications of Polymeric Materials

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ABSTRACT

Polymers constitute an extremely large class of materials generally based on carbon chemistry. Their long chain structures and unique molecular architecture make them distinct from metals and ceramics and provide them with a very wide range of properties. Polymers are also easily modified by the addition of other materials (fillers) to provide an almost limitless range of possibilities. Polymeric materials are the basis for many spacecraft components such as adhesives, circuit boards, temperature regulating "blankets", lubricants, coatings, electrical insulation, paints and high stiffness composites. As a class of materials, they continue to evolve, with further advances in both performance and applications. Current developments of micron thickness films may eventually become enabling for certain types of spacecraft (solar sails), which will be the cornerstone of future missions such as the challenging Inter-Stellar Probe (ISP).

INTRODUCTION

Polymers consist mainly of organic (carbon-based) molecules that are synthesized as very long chains. The high molecular weight and molecular entanglement of these materials gives rise to their unique properties. These include toughness, resilience, low density, high and low melting points, ability to be molded, electrical resistance, and many other properties that may be varied over very wide ranges. Due to their enormous variety of available properties, polymers find use in a wide range of spacecraft applications. These include thermal blankets, thermal control paints, adhesives, lubricants, paints, circuit boards, coatings, and insulating coatings. In the following sections, polymers will be discussed within the areas of their major use in spacecraft.

REQUIREMENTS

Apart from the wide range of useful properties that polymers offer, they must meet the requirements of in-space usage. These requirements include: (a) capability to function in hard vacuum, (b) very low outgassing to prevent contamination of surrounding components, (c) resistance to extremely harsh ultraviolet light, (d) resistance to on-orbit charged particle radiation , (e) resistance to erosion from atomic oxygen, (f) endurance over wide temperature extremes, and (g) the ability to survive the life of the mission. Not all these requirements have to be met simultaneously, a possible exception being polymeric materials exposed directly at the surface of the spacecraft. This includes primarily thermal control paints and films used in the manufacture of thermal blankets. Safety is also a requirement, as it applies to both the instrument and to the personnel. The use of polymeric materials must always be considered in terms of how it may affect other spacecraft components. Materials cannot be used that might contaminate optics, provide an electrical short, corrode metal surfaces or adversely affect other components. In addition, manned flight operations (Space Shuttle and International Space Station) impose further restrictions on flammability, smoke generation and the evolution of toxic by-products(1).

QUALIFICATION AND ACCEPTANCE

For a polymeric material to be qualified and accepted for spacecraft use, it must firstly perform its intended function, and also meet the requirements previously listed. These requirements will vary according to use. For example, most adhesives will be used in locations where there is no exposure to atomic oxygen, ultraviolet light or charged particle radiation. In this case, these requirements become suspended. The most common requirement is outgassing. All polymers are required to pass the specifications of NASA SP-R-0022A(2) and ASTM E-595(3) which specify a Total mass Loss (TML) not exceeding 1.0%, and a Collected Volatile Condensable Material (CVCM) content not exceeding 0.1%. The final acceptance is always based on the intended use, however. As an example, proximity to an optical element operating at cryogenic temperatures may make an adhesive that passes the outgassing specification unacceptable for use due to the potential for contaminating the optical surface. Other requirements may include flammability, solvent stress-crack resistance and specified processing conditions. Many properties may be found in handbooks[4,5], and may be used to qualify a material. In cases where successful performance is critical actual tests are desirable. In cases where a compound does not meet conventional requirements but has no adverse effect on the spacecraft, it is a practice at NASA to still use the particular material by issuing a Materials Usage Agreement (MUA) signed by the Lead Engineer.

THERMAL BLANKETS

Thermal blankets are essential for regulating the temperature of most spacecraft. The blankets consist of a polymer film that is either, (a) filled with carbon black pigment to absorb sunlight, or (b) coated with a layer of vapor deposited aluminum to reflect sunlight. Many layers of these films make up Multi-Layer Insulation (MLI) that constitutes the "blanket". The films are usually based on Mylar® (polyethylene terephthlate) or on Kapton® (polyimide) films available from E.I. DuPont Company. The layers are also separated by fine scrim cloths made from Nylon® polymers. These films are also frequently coated with thin layers (500 Angstroms) of indium tin oxide (ITO) which provides a path for the dissipation of static electricity (ESD). Thermal blankets are a necessity in providing a stable range of operating temperatures, and are used on virtually every spacecraft flown.

THERMAL CONTROL PAINTS

A number of thermal control paints are available that serve the same purpose as blankets- to regulate the spacecraft temperature. These paints are either black or white and consist of pigments dispersed in an organic or an inorganic binder. The polymer binder most widely used are urethanes (black paints) or silicones (white paints). White paints have high emissivity and are used for rejecting excess heat back into space. Black paints are virtually all filled with carbon black, which not only provides for good solar absorbance (85%), but serves to protect the binder from ultraviolet light damage. Black paints are used to absorb sunlight and maintain the spacecraft at warmer temperatures. White paints use a variety of pigments, and either an inorganic binder (potassium silicate) or a polymeric silicone binder (poly dimethyl siloxane). White paints have low solar absorbance ($\alpha < 0.20$) and high thermal emittance ($\varepsilon > 0.80$) that provides a thermal ratio (α/ε) such that the temperature is kept low enough to prevent over-heating. Sometimes electrical conductivity is imposed as an additional requirement to provide electrical discharge protection. The conductivity is imparted by chemical modification of the white pigment. Calcined zinc oxide and Zinc ortho-stannate are a popular electrically conductive pigments.

ADHESIVES

Polymer based adhesives are widely used throughout most spacecraft. Applications include structural bonding, wire and cable staking, lamination of optical elements, and thread-locking compounds used to prevent loosening of fasteners under high vibration conditions. The most widely used class of adhesive is the two-part epoxies, in which two liquid components are mixed, and then set (cure) to a hard, tough, adherent solid. The epoxies are also easily modified by the addition of fillers, and can provide adhesives with low coefficients of thermal expansion (down to 30 parts-per-million per degree Kelvin), excellent adhesion to metals and other plastics, high temperature capability (to 300°C) and cryogenic utility to liquid helium temperatures (4°K). Large numbers of adhesives are commercially available for spacecraft applications, and pass the basic requirements for low outgassing, bond durability and wide temperature range. In semiconductor uses, adhesives are also available with extremely low residual chloride ion contents (below 30 parts-per-million) to prevent catalytic corrosion of electrical contacts on silicon dies and VLSI circuits. Other specialty grades of adhesives include electrically conductive and thermally conductive types. These compounds are usually filled with carbon or silver powders to impart electrical conductivity, or with alumina, boron nitride, and (sometimes) diamond dust to provide a thermal coupling across two surfaces. The intimate surface contact and good adhesion of these specialty polymers is often the only way to achieve thermal or electrical continuity between uneven surfaces. Transparent and ultraviolet curable adhesives constitute another specialty type of adhesive. These adhesives are used for bonding together optical elements, such as lenses and fiber optic devices.

POLYMERS FOR ELECTRONIC COMPONENTS

Polymers in one form or another are widely used in electronics components and electronic packaging. These applications include the following:

(a) **Circuit boards**. With the exception of specialty ceramic boards for ultra high frequency electronics, circuit boards are virtually all based on glass cloth impregnated with polymer resin. A classic example is circuit board NEMA G-10, an epoxy impregnated glass cloth. Recently, new circuit board materials based on quartz cloth and poly(cyanate) resins have been found to give dielectric constants as low as 2.9 and permit much higher frequencies to be achieved than with conventional epoxy boards.
(b) **Conductive adhesives** are usually based on powdered silver filler, are widely used as die-attach compounds are used for spot bonding of electronic components, especially where confined spaces or soldering temperatures are prohibitive.
(c) **Wire insulation** is virtually all based on polymers. Teflon is widely used due to its chemical inertness, however it suffers from poor radiation stability. Recently, new insulations based on cross-linked polymers of vinylidene fluoride (PVDF) have been developed for wire and cable insulations for high radiation environments. Applications include RTGs (Radio-isotope Thermal Generators) and high radiation environments such as Jupiter orbiters. To date, cable insulations have been tested to 500 megarad doses without detectable deterioration.
(d) **Conformal coatings** are used on almost all circuit board assemblies to provide resistance to chemical corrosion and create an insulating layer across the surface. These coatings are usually based on two-part urethane chemistry that are mixed and then dipped, or sprayed onto circuit boards. Very thin conformal coatings are also created with the application of cyclophane (Parylene®) that is deposited by vacuum, and polymerized directly on the surface.
(e) **Miscellaneous** electronic applications include heat-shrinkable tubing to insulate connectors, connector potting compounds, cable ties and lacing tapes, and RF absorbing compounds. This last category is becoming more widely used as spacecraft missions expand into sub-millimeter observation ranges. RF absorbers usually consist of a silicone resin containing precisely controlled particles of ferrite compositions. Internal electrical fields then result in efficient absorption of sub-millimeter and infrared radiations and result in improved signal-to-noise ratios.

COMPOSITES FOR STRUCTURAL APPLICATIONS

Composite materials based on high modulus graphite fibers dispersed in polymer matrix resins have become a standard construction material for spacecraft(6). They are most widely fabricated as laminates, with the graphite fiber/resin layers alternating in direction over a number of angles. This construction is intended to balance the mechanical properties, and results in a "quasi-isotropic" laminate. Composite use includes spacecraft busses, torque tubes, optical benches and other high dimensional stability components. Composites offer high strength to weight and stiffness to weight ratios that reduce spacecraft mass while improving mechanical performance. Other major considerations in selecting are moisture absorption and impact resistance. A minor impact damage (usually called barely visible damage) can degrade the compressive strength of a typical epoxy composite by more than 50%. Water absorption must also be considered in terms of both dimensional stability (the coefficient of moisture expansion) and the amount of outgassing. Typical epoxy composites may gain up to 2.5% water at saturation, and have an expansion (quasi-isotropic, in-plane) of 200 parts-per-million per percent water content. A conspicuous use of composite construction is the metering truss of the Hubble Space Telescope (M55J® graphite fiber with 954-3® epoxy resin). New classes of composites based on very high modulus (>70 msi) fibers and poly(cyanate) resins offer very low water absorption, more uniform cure, higher dimensional stability and excellent radiation resistance(7). The water absorption of commercial poly(cyanates) is about 0.3% at saturation, and the moisture expansion (quasi-isotropic, in-plane) is less than 100 parts-per-million per percent absorbed water. Many spacecraft constructions are moving to cyanate-based composites due to these improved properties. Despite the higher cost and more demanding fabrication techniques, composites offer lower mass, high specific stiffness, high specific (tensile) strength and high dimensional stability that is practically unavailable with any other class of materials. In the past decade, composite materials have become a standard replacement for aluminum, titanium and steel in spacecraft with demanding mass and stability requirements.

MISCELLANEOUS

Many applications of polymers exist in miscellaneous applications. Certain classes of lubricants (poly-alpha olefins, poly-aryl ethers) are all polymer based, and offer high lubricity, high radiation resistance (up to 10^9 rads) and extremely low vapor pressures (down to 10^{-13} torr). Marking inks are also widely used for identifying spacecraft components. These are normally based on two-part epoxies dispersed in a solvent.

The solvent in the ink is then baked off to leave a non-volatile marking. Other uses of polymers include bearing cages, elastomeric seals, vibration dampers, thermal coupling gaskets, and anti-migration coatings. Anti-migration coatings are polymers with very low surface energy (12 dynes/cm) that prevent the spread of lubricants and oils over surfaces that must be kept clean.

FUTURE APPLICATIONS AND MATERIALS DEVELOPMENT

Thin Films

Future applications of polymeric materials may include extremely thin films for programs such as inflatable antennas, solar sails, very large area reflectors and missions in the "Gossamer" class of programs currently being pursued by NASA. The thin films are required to be in micron thickness ranges, have areal densities of 5 grams per square meter (or less), and withstand handing and deployment operations without sticking or tearing. Recent developments have shown the possibility of manufacturing continuous films as thin as 0.25 microns. An additional concept that might further enable this materials challenge is a "fugitive mass" coating. This is a polymer based coating that could be applied to thin films to improve their handling and deployment, but then evaporates from the surface when exposed to the space environment. Currently, the classes of poly(silanes) and poly(butyl methacrylate) are being evaluated for this purpose. Both are attacked by ultraviolet light and are degraded to gaseous products and result in decreased mass of thin films used in solar sail applications.

Shape Memory Polymers

Development efforts are in progress leading to "shape memory polymers" for space-deployable spacecraft. These are open-celled elastomer foams that are fabricated to the desired shape, compressed to a low storage volume, cooled to below their glass transition temperature (T_g), and then stored prior to launch. After space deployment, the "frozen" foam heats to above its T_g and expands back to its full dimensions. Elastomer foams offer the benefits of being self-deploying, have excellent vibration damping, have low thermal conductivity and low thermal mass, are resistant to micrometeorite punctures and self-correct to their original dimensions in response to transient loads.

Electroactive polymers

Electroactive polymers are also under development as actuators and "smart structures" for very advanced applications such as sample return missions. These polymers consist of fluorinated ionic membranes with electrodes applied on both sides. Applying an electric field to the film causes ions to accumulate on one side, resulting in a bending stress, and movement. The Jet Propulsion Laboratory has already demonstrated robotic technologies based on these materials, and is continuing with development programs.

Electrochromic Films

Electrochromic films are very much in the experimental stages. These are multi-layer polymer films that change their thermo-optical properties in response to an applied voltage. The layers are coated with a transparent conductive layer (indium tin oxide), a polymer gel electrolyte and a back coating with a reversible oxidation state, and reversibly dark color. These films provide variable infrared emissivity in the range of 0.35 to 0.75, and may find use as "smart surfaces", providing thermal control of spacecraft in changing orbital conditions.

CONCLUSIONS

Polymeric materials have played an essential role in spacecraft since the very first launch in the 1960's. In the three decades that followed many more materials became available, with increasing numbers of applications, definitions of their performance and specifications for their use. Despite this fact, they continue to be developed with ever-increasing capabilities, and may eventually become enabling for certain spacecraft (eg. solar sails) without which these missions will not be possible.

ACKNOWLEDGEMENT

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. NASA NHB 8060.1 " Flammability, Odor and Offgassing Requirements and Test Procedure for Materials in Environments that Support Combustion."
2. NASA SP-R-0022A, "Vacuum Stability Requirements of Polymeric Material for Spacecraft Application"
3. ASTM Standard E595, "Test Method for Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment."
4. NASA MSFC-HDBK-527/JSC 09604, "Materials Selection List for Space Hardware Systems."
5. NASA Reference Publication 1124, "Outgassing Data for Selecting Spacecraft Materials," William Campbell and John Scialdone, September, 1993.
6. MIL-HDBK-17, Composite Materials Handbook," 1999
7. "Advanced Composite Materials", Manufacturer's literature, YLA Inc., Benicia, California